Transport Theory for Propagation and Reverberation

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LONG-TERM GOALS

Development of computationally efficient modeling methods for shallow water propagation and reverberation that can account for the effects of multiple forward scattering from waveguide boundary roughness and volume heterogeneity such as internal waves.

OBJECTIVES

Our objective in FY11 was to improve the generality of our previously developed shallow water propagation model based on transport theory to include reverberation. An additional objective in FY11 was to resolve a deficiency observed in previous results when transport theory was extended to include range dependent bottom depth in one-way propagation. The results showed a deficiency in the intensity of the field penetrating into the bottom in response to forward scattering from the sea surface. Transport theory, as we have developed it, can account for the effects of multiple forward scattering from boundary roughness. The emphasis of this work is on the mid-frequency range (1-10 kHz) where effects of forward scattering can be important.

APPROACH

Accurate propagation and reverberation modeling is important for many prediction methods that are important for Navy applications and for underwater acoustics systems development. While acoustic propagation and reverberation modeling has been extensively developed for many years, significant limitations still exist on current capability, particularly in the area of computation speed. In addition, the modeling problem increases in complexity as the frequency is raised from the low frequency region (< 1 kHz) to the mid frequency region (1–10 kHz). At mid frequencies (and higher) the effect of forward scattering from the sea surface and bottom has a greater effect on propagation and reverberation than in the low frequency region, especially in shallow water environments.

The available options for modeling forward scattering in propagation are very limited, and are largely confined to computationally intensive methods that can yield benchmark solutions for certain simplified problems. When PE is used for practical propagation modeling, only large-scale bathymetry variations are included with small-scale boundary roughness ignored, and internal waves are also generally ignored. Even the simple expedient of using a loss at the boundary to approximately account for boundary roughness is not conveniently included in PE propagation simulations. Similarly, normal

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mode methods generally ignore mode coupling due to boundary roughness in forward propagation, and in reverberation simulations only a single scattering (the backscattering) is included. In order to include the stochastic effects of boundary forward scattering and internal wave forward scattering in propagation simulations, investigators have typically applied a full-wave method, such as PE, and performed propagation simulations using many realizations of the fluctuating environment in a “Monte Carlo” approach. Averaging the results over the set of realizations can then give accurate results for averages (or moments) of the field, and by using a sufficient number of realizations even pdfs of field amplitudes or intensities can be obtained. In the case of boundary roughness scattering, simulations using the finite element method have also been used. The computational demands for full-wave Monte Carlo simulations for propagation and particularly for reverberation are severe.

Instead of doing time consuming Monte Carlo simulations, much faster solutions for field moments can be obtained if equations governing the evolution of the moments themselves can be obtained and solved. Any method that works with evolution equations for the moments of the propagating quantities can be described as a “transport theory,” though not always referred to as such. While transport methods have been applied to propagation through internal waves, there has been no related extension to propagation in the presence of rough boundaries (except for work by our APL-UW group) or to reverberation for either case. The historical emphasis on internal waves may be due to their importance even at low frequencies where boundary scattering is less important. For mid frequencies forward scattering from both internal waves and boundary roughness are of importance.

Therefore, the need exists for much faster computational approaches for obtaining moments of the field for propagation and reverberation at mid frequencies that can account for boundary and internal wave scattering. Past work has been restricted to one-way propagation in the range independent case. In the current project this is being extended to range dependent propagation and full reverberation scenarios. Our approach is based on expanding the acoustic field in modes, and therefore would most readily apply at mid-frequencies and below, and in relatively shallow water environments such as on the continental shelf.

We have focused on the case where forward scattering is due to scattering from sea surface roughness. Evolution equations are obtained for the first and second moments of the mode amplitudes, accounting for mode coupling due to scattering from a rough sea surface using first-order perturbation theory [1]. Comparisons with rough surface PE simulations [2] have been used to verify the accuracy of the transport theory method for one-way propagation. It should be kept in mind that transport theory is much faster than full wave approaches that use a Monte Carlo method with many rough surface realizations. Also, any number of forward scattering interactions can accounted for as the field propagates along the waveguide.

WORK COMPLETED

Transport theory has been extended from one-way propagation scenarios to full reverberation modeling, and important effects of surface forward scattering are included. The reverberation can be due to scattering from the sea surface, the sea floor, or both, but at this stage forward scattering during propagation out and back from a given scattering patch is due only to the rough sea surface. For most environments and at mid frequencies sea surface forward scattering will be much more important to include for reverberation modeling than bottom forward scattering. Reciprocity is used to relate the transmission amplitude from the source to a given scattering patch on the surface or bottom to the

corresponding transmission amplitude on the return path. [The transmission loss in dB is −20 log (transmission amplitude).] For bistatic reverberation, transport theory would be used in model forward propagation twice, one from the source position and one from the receiver position. For monostatic reverberation, only a single forward propagation runs is required. Scattering theory based on perturbation theory is used to couple forward-going mode amplitudes to backward-going mode amplitudes at a given scattering patch. As shown in the Results section, surface forward scattering can have very important effects on reverberation level at mid frequencies.

In the year end report for FY10, results were shown for the extention of transport theory to the case of a slowly varying bottom depth, including the effect of sea surface forward scattering. Adiabatic modes were used to treat the slow range dependence, and linear interpolation between mode sets at different bottom depths was used to account for changes in mode horizontal wave numbers and in the mode functions with range. The results showed a deficiency in the intensity of the field penetrating into the bottom in response to forward scattering from the sea surface. The penetrating field is mainly made up of modes with higher mode numbers than the “trapped modes,” and sea surface forward scattering excites these higher modes, leading to continual loss into the bottom. Investigation showed that the linear interpolation of the imaginary part of the horizontal wave number for these higher modes led to the problem. For this set of “non-trapped modes,” the mode structure in complicated, with “promoted modes” or true modes interspered with continuous modes, and the imaginary parts of the horizontal wave numbers differ dramatically between to two types of modes. Because of this, straighforward linear interpolation between mode sets with different bottom depths was not appropriate. It was also found that the continuous modes were not excited either by the original source or by forward scattering at the sea surface, and could effectively be ignored. Therefore, the modes were first reordered based on the imaginary parts of the horizontal wave number, effectively excluding the continuous modes, and then interpolations between mode sets at difference bottom depths could be used to account for the range dependence of the adiabatic modes. This procedure removed the original deficiency that had been oberved.

RESULTS

For the reverberation example presented the frequency is 3 kHz, the rough sea surface is modeled with an isotropic Pierson-Moskowitz roughness spectrum, the bottom is taken to have the Reverberation Modeling Workshop “typical roughness” model [3], the sound speed in the water is 1500 m/s, the sound speed in the sediment is 1600 m/s, the density ratio (sediment/water) is 2, and the attenuation in the sediment is 0.5 dB/λ. The water depth is 50 m, and another 50 m of sediment is included in the computation domain with the result that continuous modes are represents as closely spaced discrete modes. A 3-D geometry is assumed using the usual “N$\times$2D model” where azimuthal divergence is included, but all propagation and scattering is confined to the 2-D vertical-range plane. A point source and point receiver are co-located at a water depth of 25 m. Incoherent mode superposition is used for the propagation out and back. This yields smooth reverberation curves for simplicity, but coherent superposition could just as well be used for the first moment contribution to yield the complicated waveguide propagation structure.

Figure 1 shows two sets of reverberation curves out to a time of 60 s, the lower set of three curves is for surface reverberation only, and the upper set is for surface and bottom reverberation. For the lower set the bottom is taken as flat with no roughness. For this example the wind speed is 7.7 m/s (15 knots) giving an rms wave height of 0.31 m, and a significant wave height of 1.3 m or about 4.2 ft. The source

waveform was taken to be a Gaussian modulated CW with a pulse length determined by a 3 dB-down bandwidth of 3 kHz/20, or 150 Hz. The maximum amplitude at the peak of the pulse (at pulse center) is 1 μPa at 1 m. To obtain the equivalent reverberation level for a rectangular pulse with source level of 0 dB re 1 μPa at 1 m with a pulse length of 1/(150 Hz), one should add 6.29 dB to the curves shown.

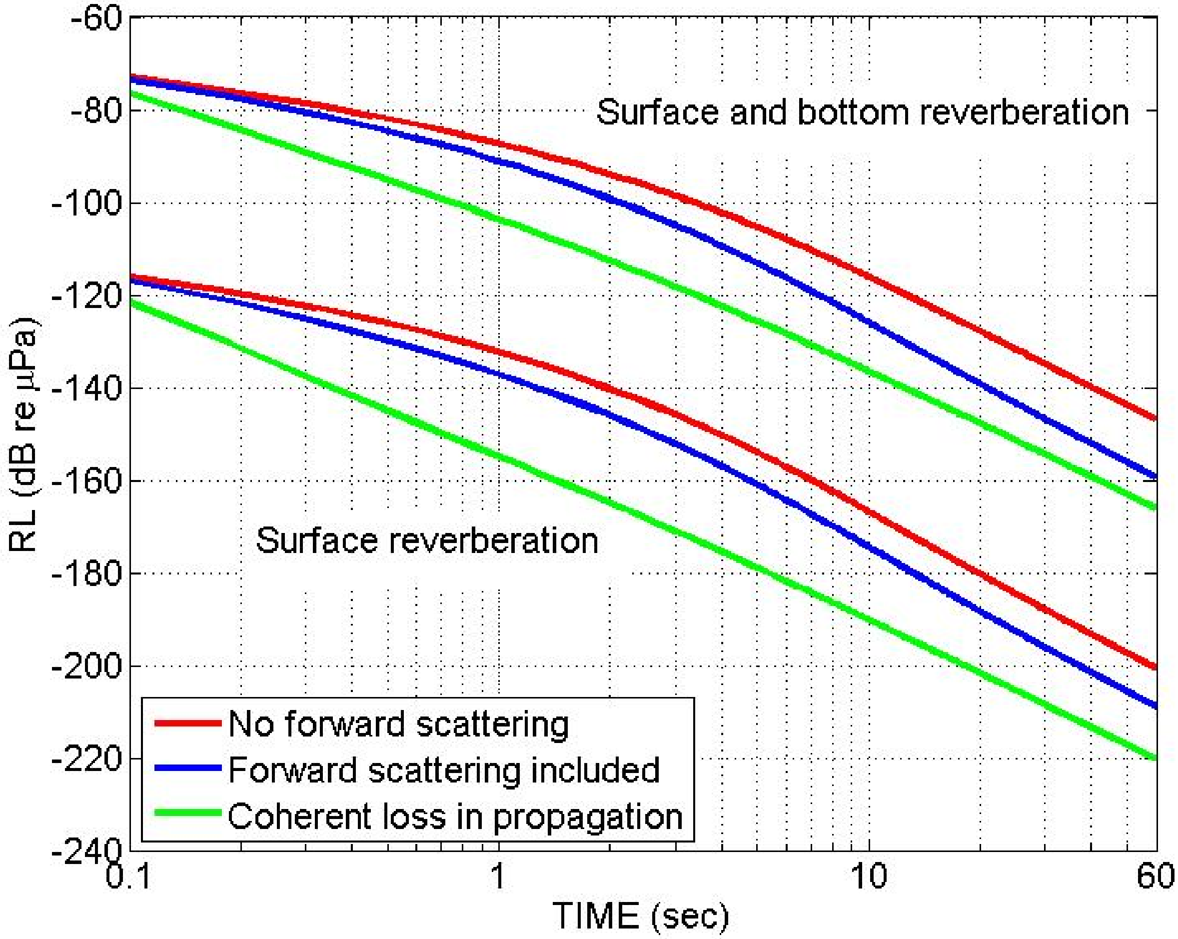

Figure 1. Reverberation predictions obtained with transport theory. The red curves ignore all effects of boundary roughness during propagation. The blue curves account for surface forward scattering. The green curves approximate the effect of surface forward scattering in terms of a coherent loss.

Consider the surface reverberation curves first. When forward scattering is ignored (red curve) the reverberation prediction is too high because the effect of sea surface roughness in scattering energy out of the waveguide is being ignored. Thus, the effect of enhanced mode stripping due to scattering is not being taken into account. The solid green curve is the transport theory result based on the first moment of the field, and is equivalent to assuming a coherent scattering loss at the sea surface. This result is too low compared to the blue curve that includes surface forward scattering. The effect of forward scattering is to enhance the reverberation level (up to 20 dB in this case) over that given using a coherent loss model. Physically, this occurs because forward scattering is dominated by scattering

relatively close to the specular direction. Therefore, while this scattering can result in energy being scattering above the critical angle (about 20 deg in this case) and then lost into the bottom, this mainly occurs through repeated scattering that in a random walk type of process eventually leads to scattered energy being removed from the waveguide. But it also leads to a significant residence time of this energy, as it is being repeatedly re-scattered while it has relatively high grazing angles, significantly increasing the reverberation level.

In many cases bottom reverberation dominates over surface reverberation, as shown by the upper set of curves, even for this isovelocity sound speed profile. However, the effect of surface forward scattering is still very important in modeling the reverberation correctly, since it enhances the higher grazing angle energy incident on the bottom. Neither option of ignoring effects of surface forward scattering (red curve) or using a coherent loss for the surface interaction (green curve) comes close to the result obtained by modeling the effect of surface forward scattering in detail (blue curve). These reverberation results have not been obtained before, and clearly show the importance of detailed modeling of surface forward scattering at mid frequencies on reverberation modeling. For these results forward scattering from roughness on the bottom has not been modeled, but under most conditions it can be expected to be significantly less important that surface forward scattering. Treatment of bottom forward scattering with transport theory is a topic of future work.

Finally, an example of propagation in a range dependent waveguide is shown in Figure 2. The problem considered is CW propagation at 3 kHz in two space dimensions with a source at mid depth. A rough sea surface is described by a 1-D Pierson-Moskowitz roughness spectrum for a wind speed of 7.7 m/s (15 knots). The waveguide depth varies linearly from 50 m to 45 m at a range of 12 km. The sea floor sediment has sound attenuation of 0.5 dB/wavelength. The sound speeds are 1500 m/s in the water and 1600 m/s in the sediment. The computational region extends 50 m into the sediment, and continuus modes are represented as closely spaced discrete modes. For a 50 m depth there are 70 trapped modes. A total of 114 modes, starting with 200 modes and then re-ordering based on the imaginary part of the horizontal wave number, have been used to display the field penetrating into the sediment at grazing angles above the critical angle. This result for the total intensity resolves the descrepancy noted in the FY10 year end report.

IMPACT/APPLICATIONS

Work in transport theory propagation and reverberation modeling should lead to improved simulation capability for shallow water propagation and reverberation in which multiple scattering from rough boundaries is properly taken into account. This capability should be particularly important in the mid-frequency range where multiple scattering effects can be important, yet where a modal description can be used. Transport theory propagation and reverberation modeling has the potential to be even faster than ray tracing, yet be able to account for scattering effects outside the scope of other efficient modeling methods.

RELATED PROJECTS

1. Reverberation Modeling Workshops, Eric Thorsos and John Perkins co-chairs. This effort has developed a set of well-define reverberation problems with consensus solutions. This has been important for testing the accuracy of transport theory for reverberation problems when forward scattering is ignored as assumed for the workshop problems.

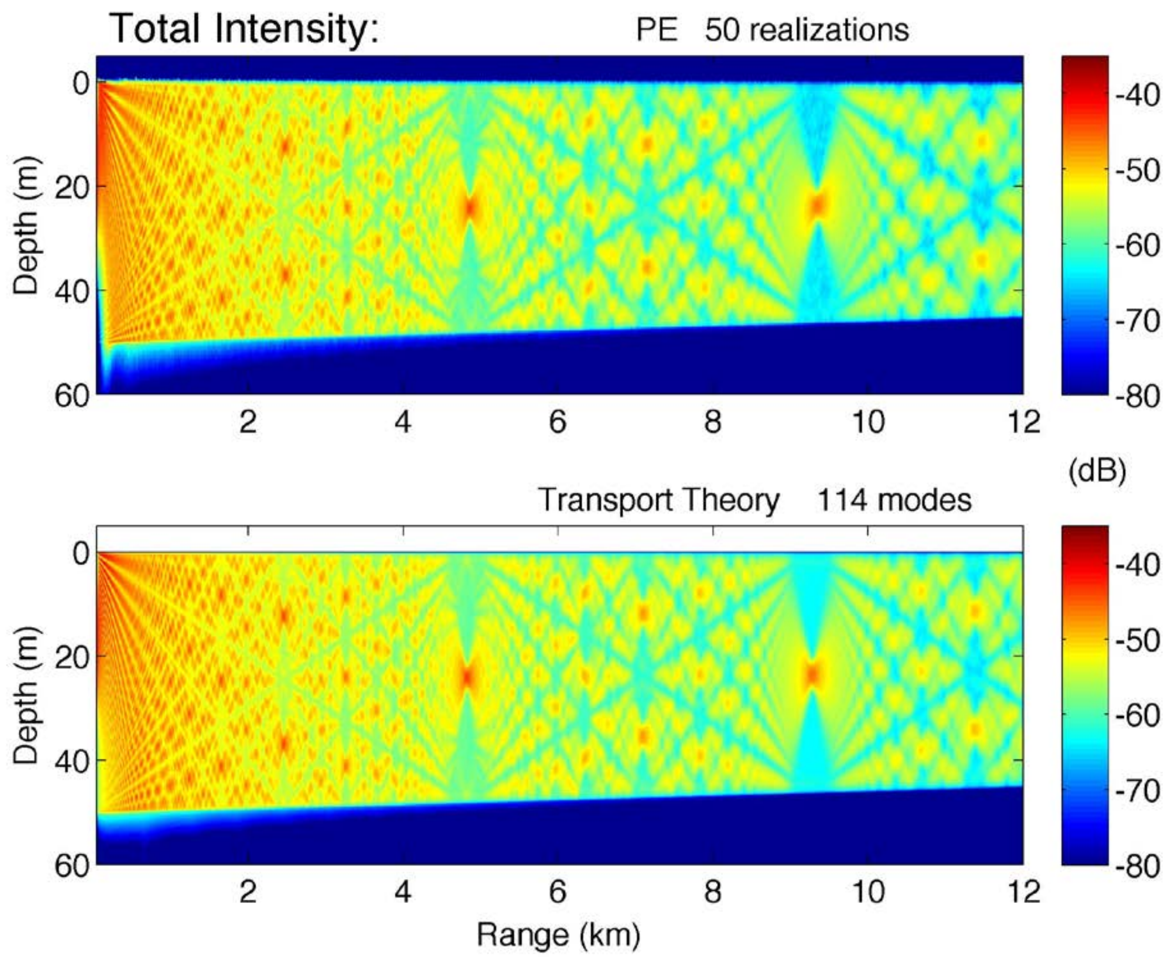

Figure 2. The total intensity for PE averaged over 50 surface realizations (top), and for transport theory (bottom) for a range dependent bottom depth and with a rough sea surface.

2. ONR (John Tague) is supporting work on extending the Sonar Simulation Toolset (SST, development under the direction of Bob Goddard, APL-UW) to lower frequencies. A PE based reverberation model is presently being developed for SST for the low frequency extension. A future possibility of utilizing transport theory propagation has been discussed in this context, with the proviso that it first requires additional development.

3. PMW-120 (Marcus Speckhahn) is supporting work on developing a model (TOTLOS) that can approximately account for effects of surface forward scattering in ray-based (such as CASS/GRAB) or mode-based propagation and reverberation models. Results for transport theory are now being used to aid in TOTLOS development.

REFERENCES

[1] E. I. Thorsos, F. S. Henyey, W. T. Elam, B. T. Hefner, S. A. Reynolds, and J. Yang, "Transport theory for shallow water propagation with rough boundaries," *Shallow-Water Acoustics*,

Proceedings of the Second International Shallow-Water Acoustics Conference, Shanghai, China, September 16-20, 2009, AIP Conference Proceedings 1272, pp. 99-105.

[2] A. P. Rosenberg, "A new rough surface parabolic equation program for computing low-frequency acoustic forward scattering from the ocean surface," *J. Acoust. Soc. Am.* **105**, 144-153 (1999).

[3] ftp://ftp.ccs.nrl.navy.mil/pub/ram/RevModWkshp

PUBLICATIONS

E. I. Thorsos, D. Tang, K. L. Williams, B. T. Hefner, J. Yang, W. T. Elam, and F. S. Henyey, "Key Issues in mid-frequency reverberation modeling and experiments," in proceedings of the 4th International Conference on Underwater Acoustic Measurements: Technologies and Results, held on the Island of Kos, Greece, 20-24 June 2011.